United States Patent [19]

Lee et al.

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[45] **Date of Patent:** Nov. 12, 1996

[54] **ZERO-VOLTAGE-TRANSITION (ZVT) 3-PHASE PWM VOLTAGE LINK CONVERTERS**

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[73] Assignees: **Center for Innovative Technology,** Herndon; **Virginia Tech Intellectual Properties, Inc.; Virginia Polytechnic Institute and State University,** both of Blacksburg, all of Va.

[21] Appl. No.: **304,661**

[22] Filed: **Sep. 9, 1994**

[51] **Int. Cl.^{6}** **H02M 7/5387**
[52] **U.S. Cl.** **363/132;** 363/40; 363/138
[58] **Field of Search** 363/37, 40, 79, 363/127, 129, 131, 132, 138; 318/762, 803

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*Primary Examiner*—Peter S. Wong
Assistant Examiner—Adolf Berhane
Attorney, Agent, or Firm—Whitham, Curtis, Whitham & McGinn

[57] **ABSTRACT**

An improved zero voltage transition (ZVT) pulse width modulation (PWM) link converter is provided which introduces a space vector modulation scheme and an auxiliary circuit which includes a commutation power supply or special switch arrangement used to discharge resonant inductor currents to zero and to recover commutation energy. In an alternate embodiment, an improved ZVT PWM link converter provides an auxiliary switch for each main switch in the converter to achieve ZVT. The novel ZVT converters provide zero-voltage switching without increasing switching action of the main switches. In this way, the advantages of PWM control is maintained. Conduction loss, turn-off losses, and voltage stress of the main switches are the same as in conventional PWM converters, but the dominant turn-on losses are eliminated, so total power losses are minimized.
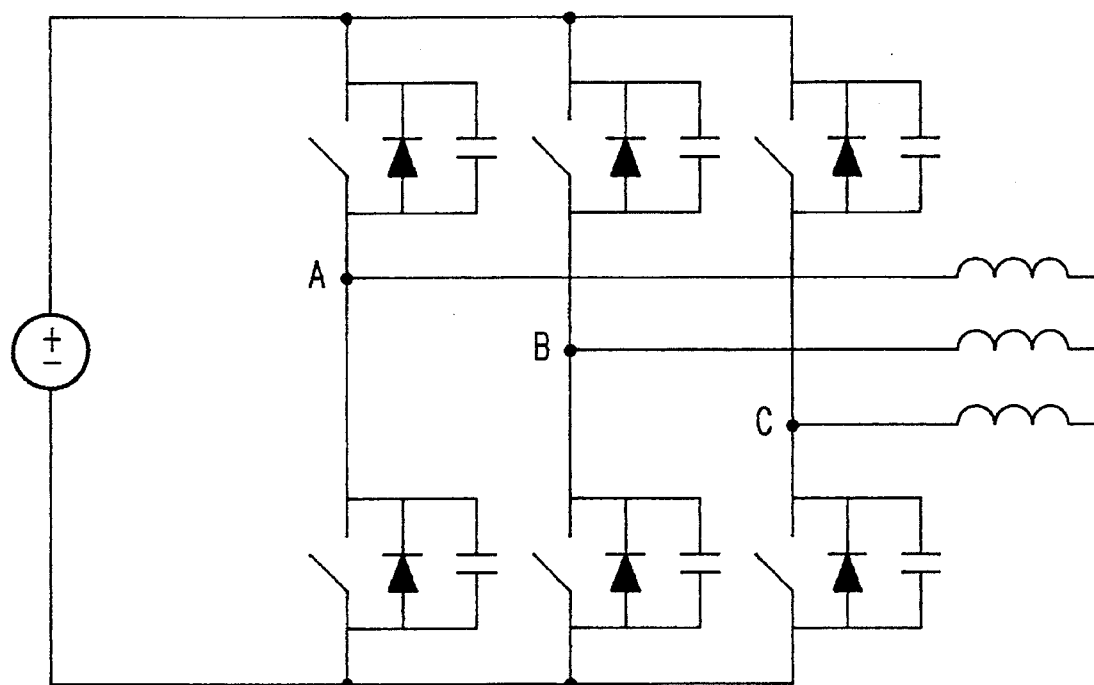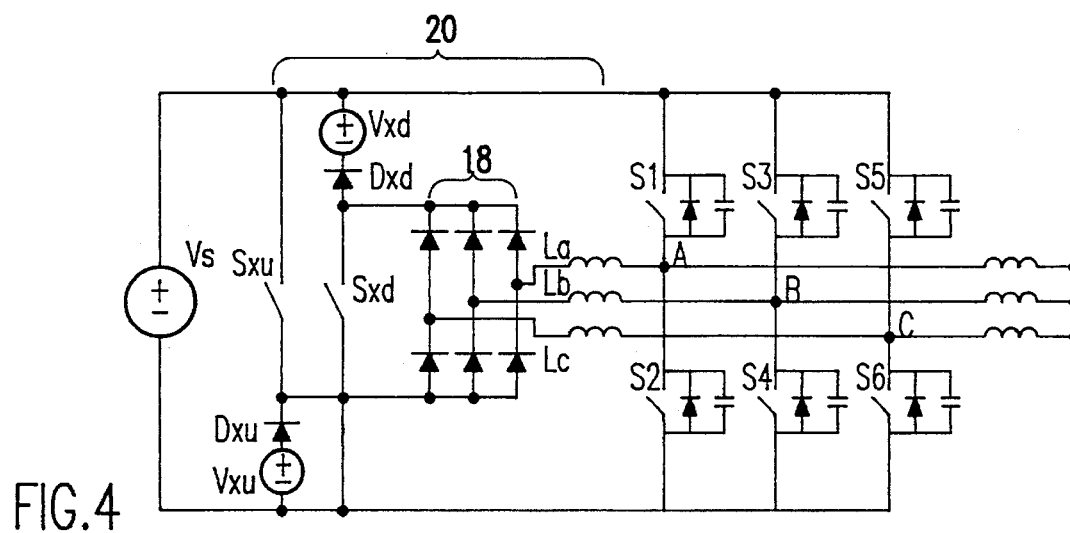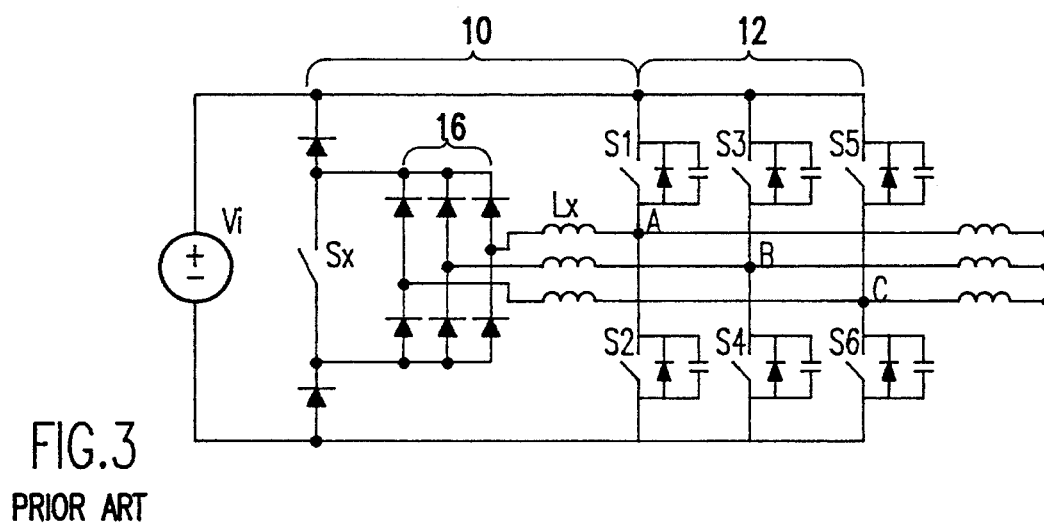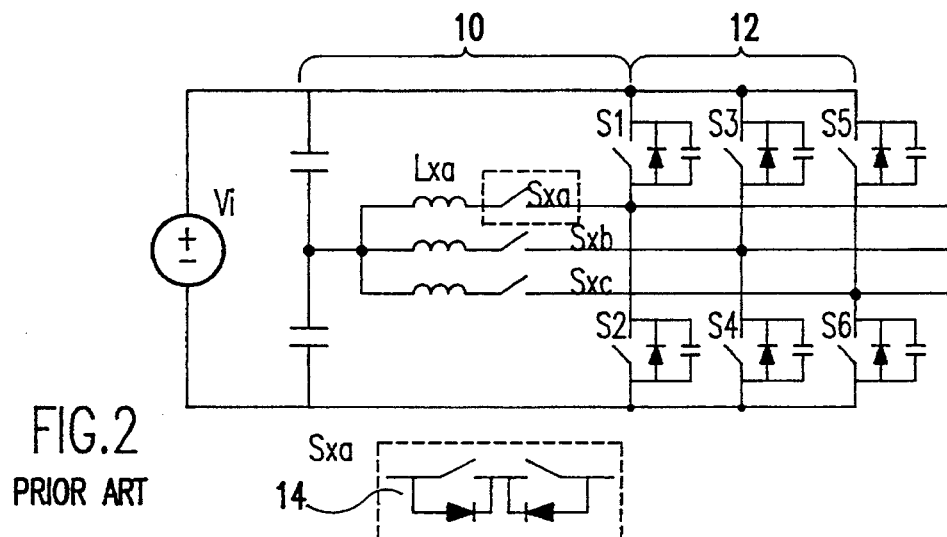
7 Claims, 14 Drawing Sheets

FIG.1
PRIOR ART

FIG.2
PRIOR ART

FIG.3
PRIOR ART

FIG.4
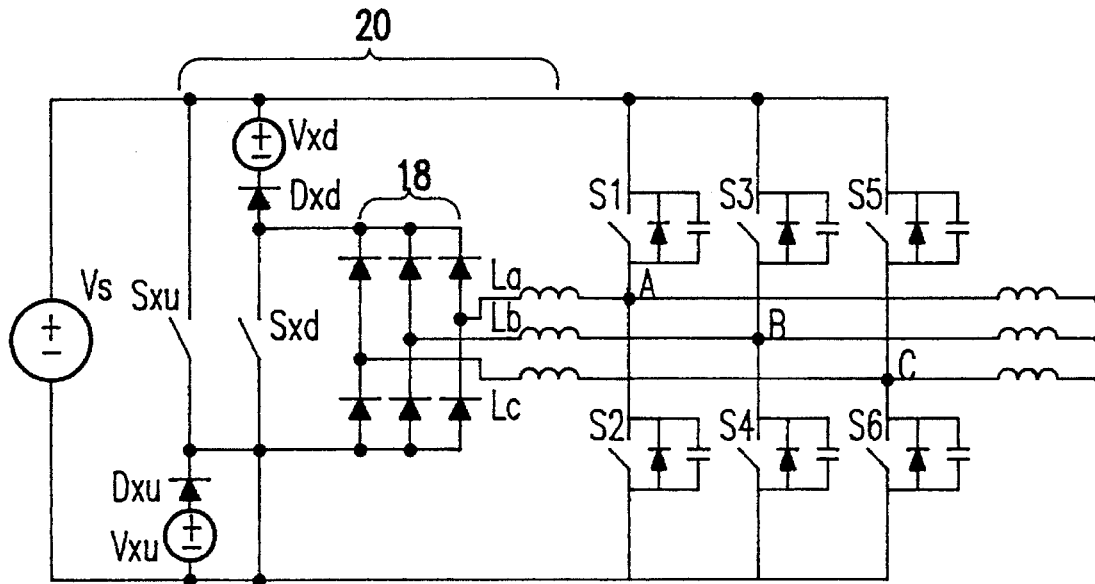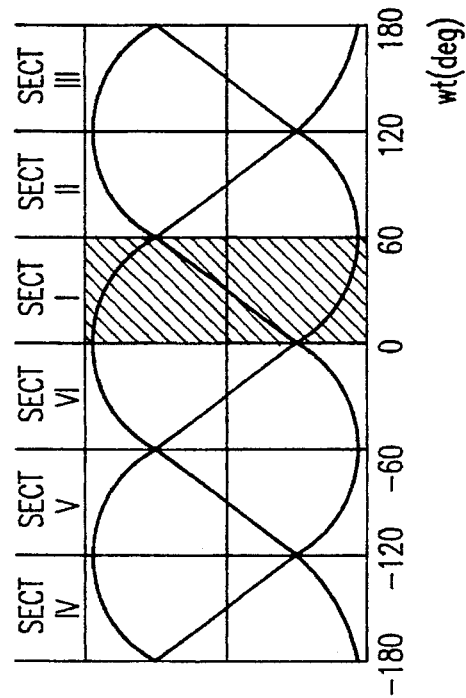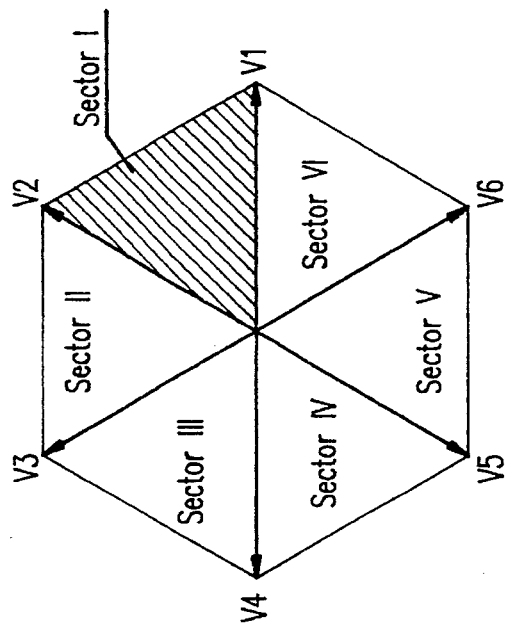
FIG.5
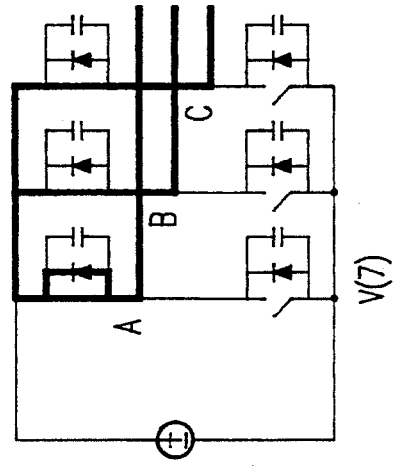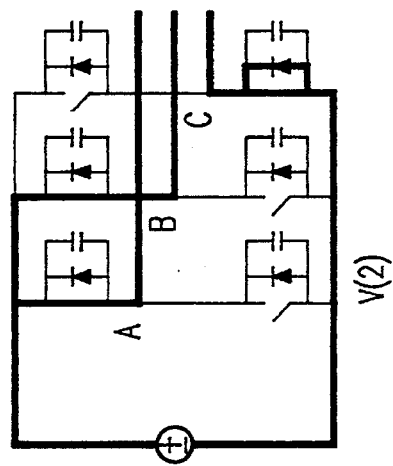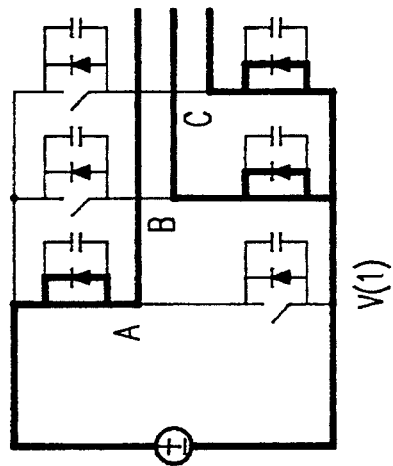
FIG.6

Switching Sequence: V(7)–V(2)–V(1)–V(7)–

V(1)

V(2)

V(7)
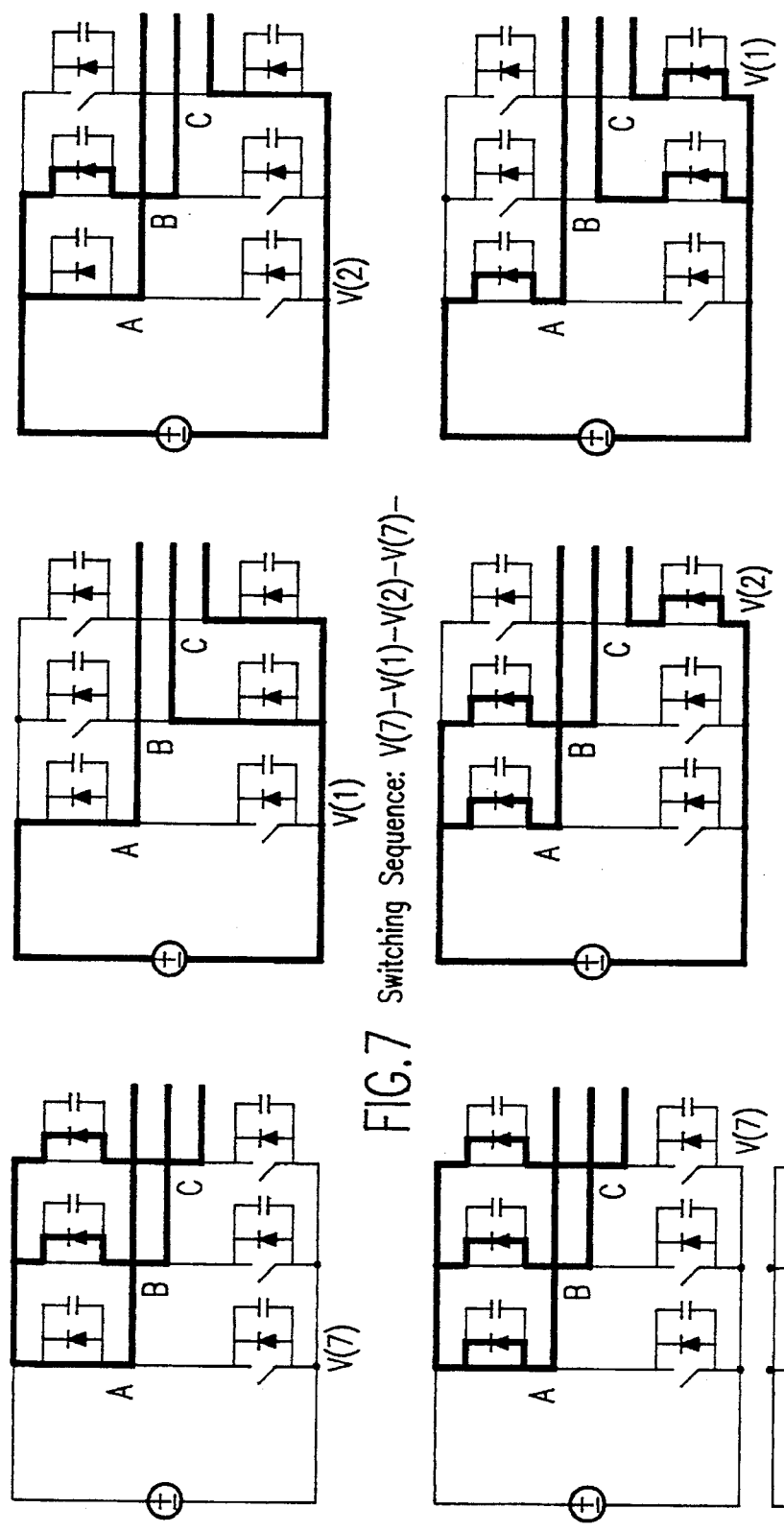
FIG.7 Switching Sequence: V(7)–V(1)–V(2)–V(7)–

FIG.8 Switching Sequence: V(7)–V(2)–V(1)–V(0)–V(1)–V(2)–V(7)–
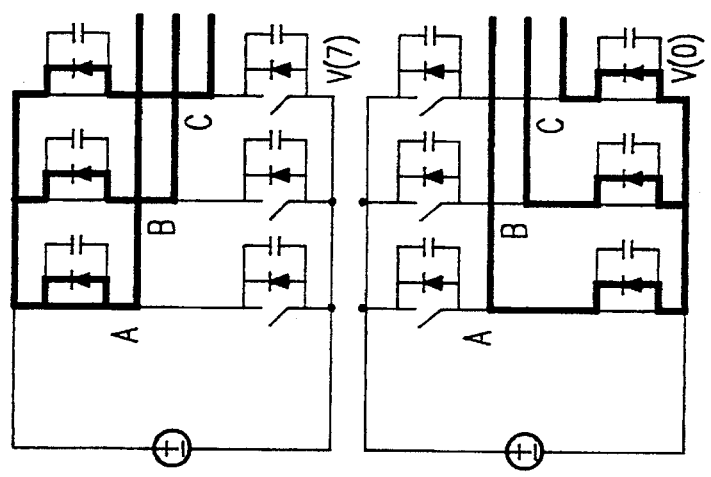
FIG.9

FIG.10

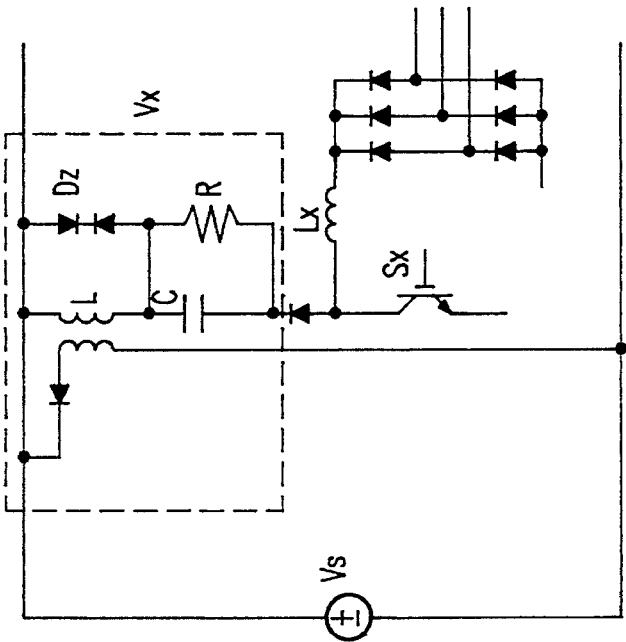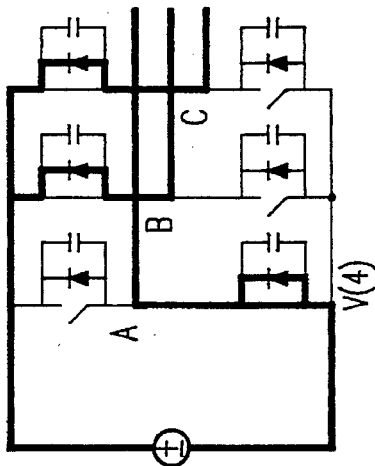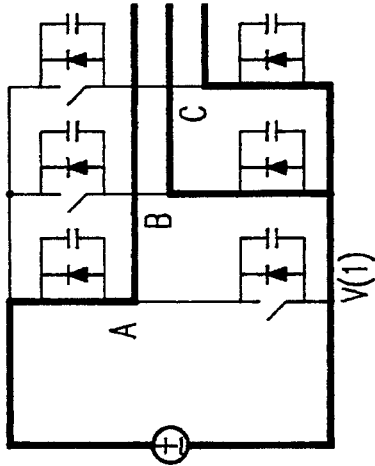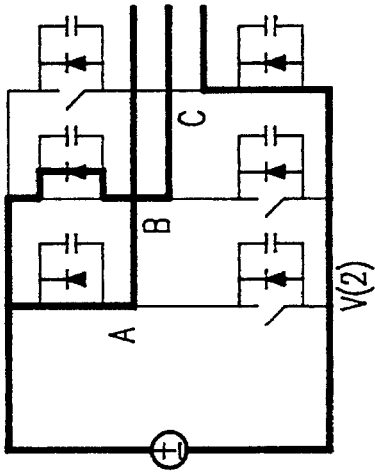Switching Sequence: V(4)–V(1)–V(2)–V(4)–
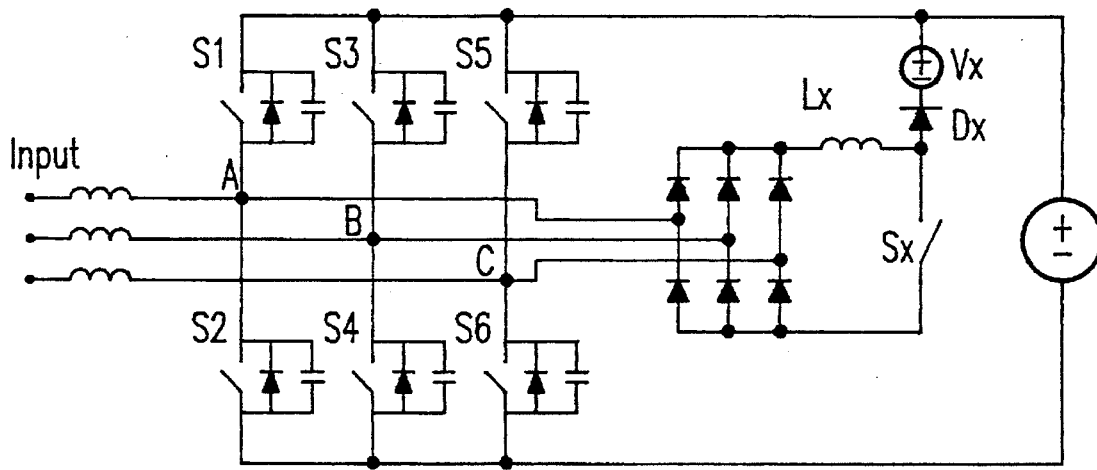
FIG.11
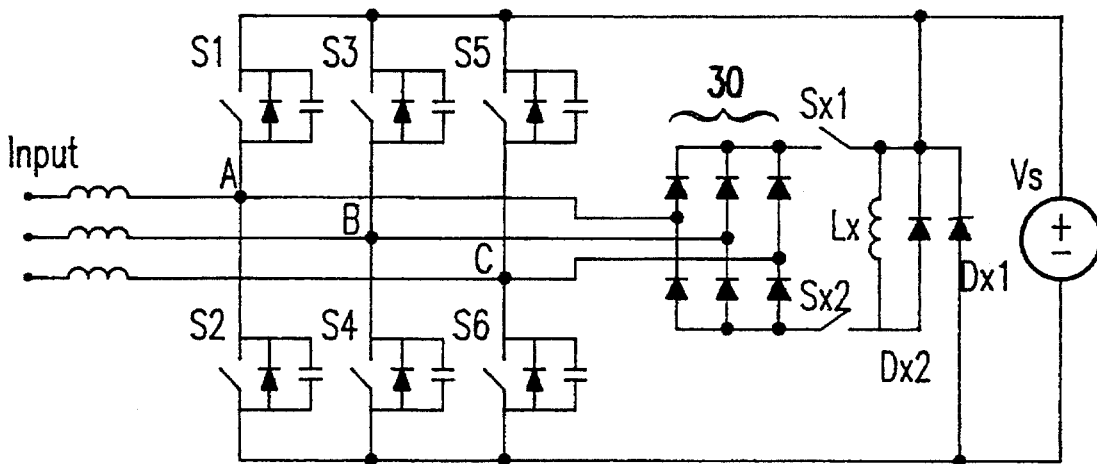
FIG.12
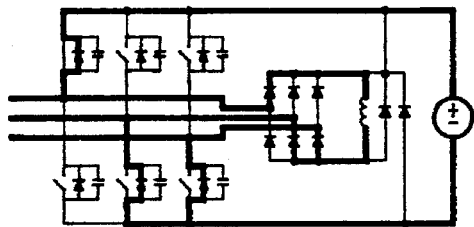
(1)

(2)

(3)
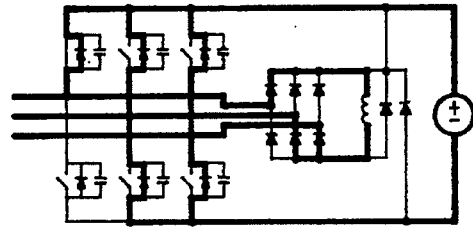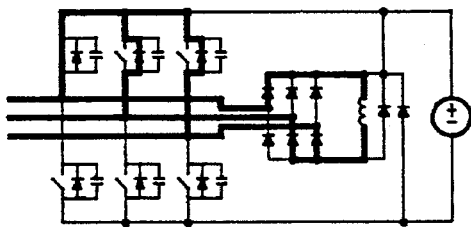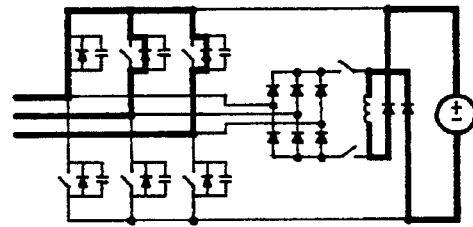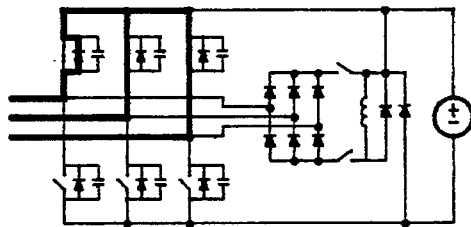
(4)

(5)

FIG.13
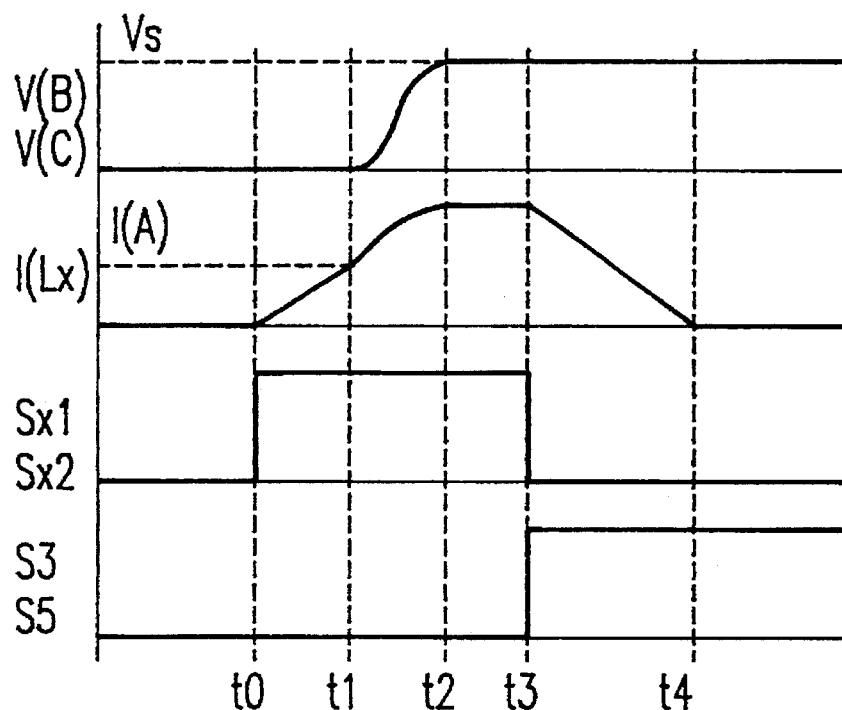
FIG.14
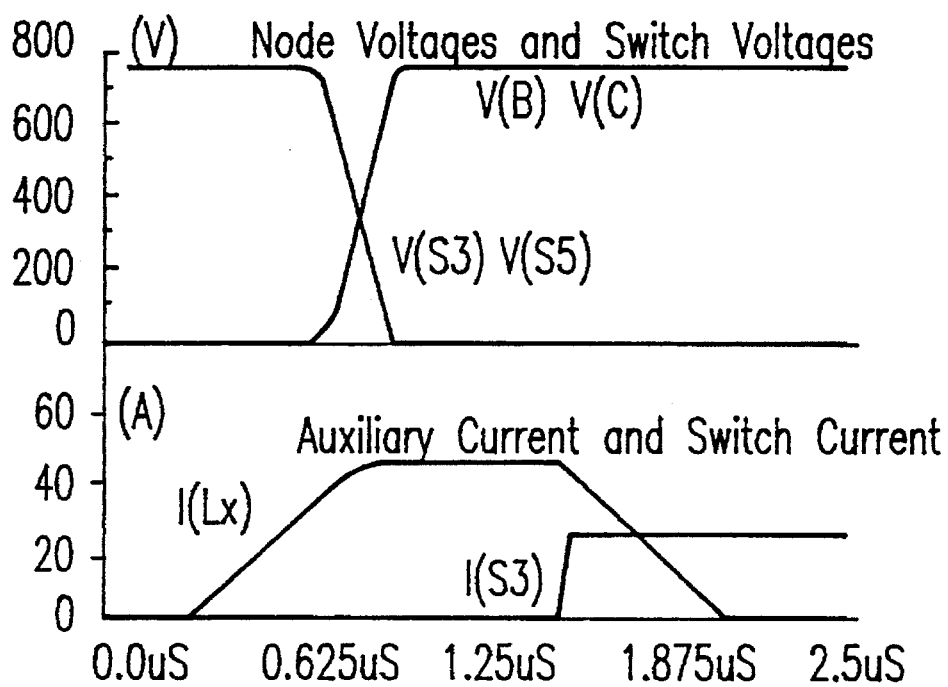
FIG.15
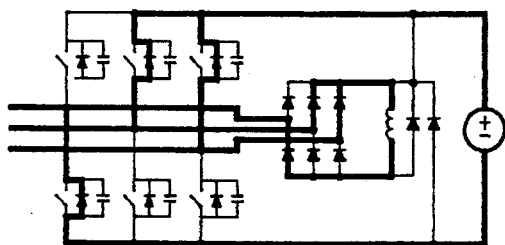
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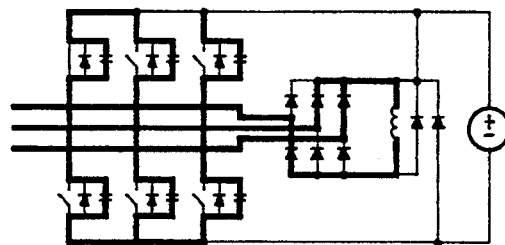
(2)
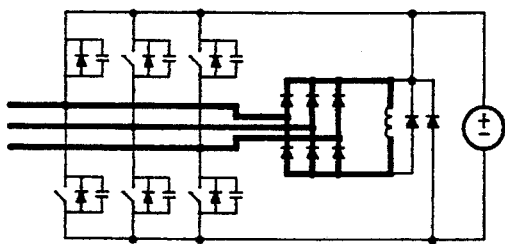
(3)
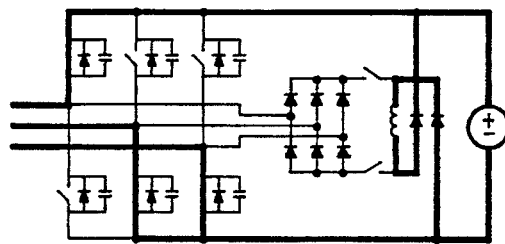
(4)
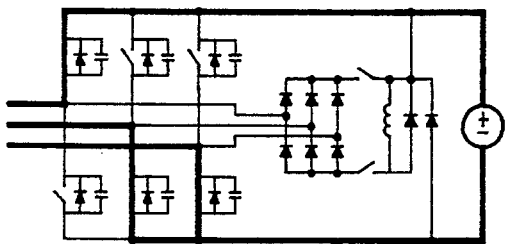
(5)

FIG.16
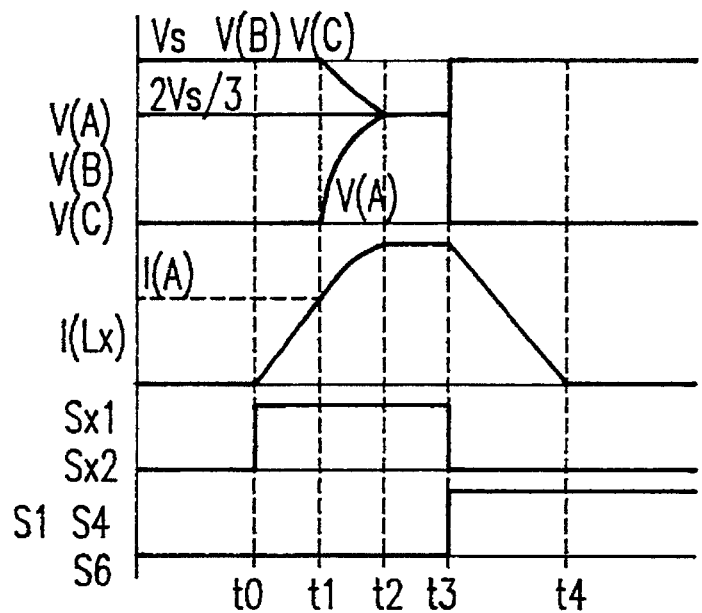
FIG.17
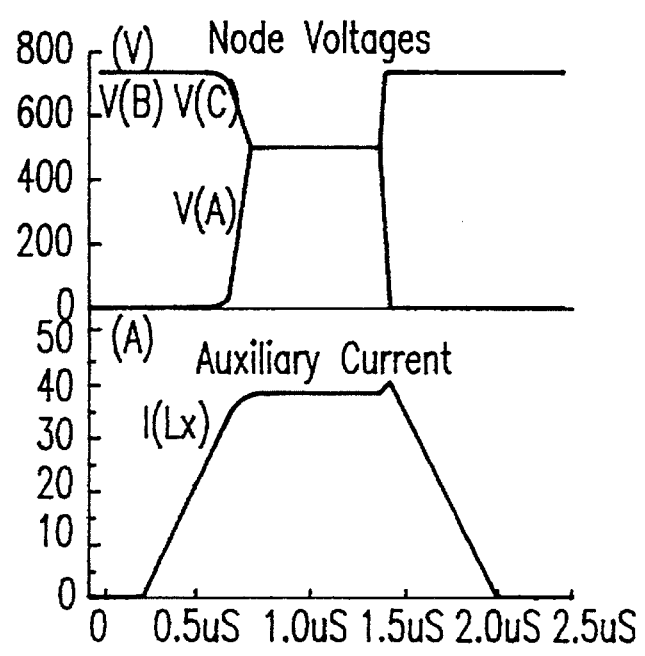
FIG.18
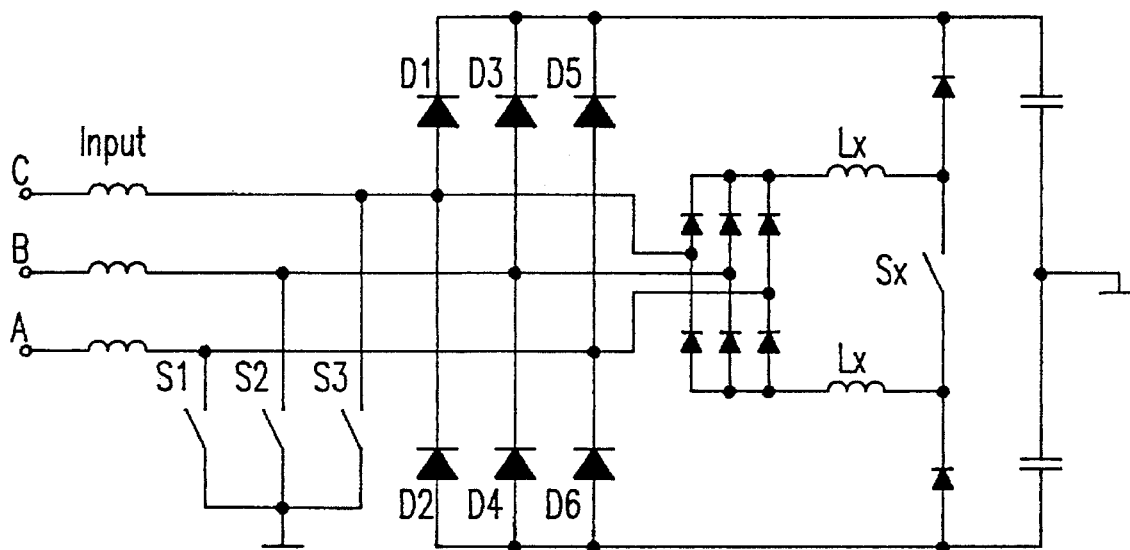
FIG.19
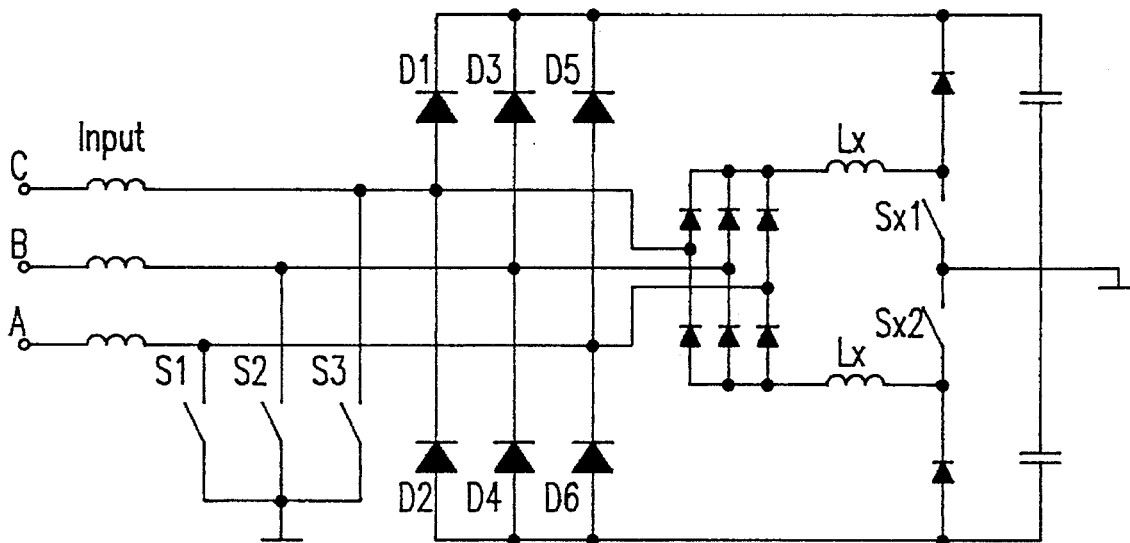
FIG.20
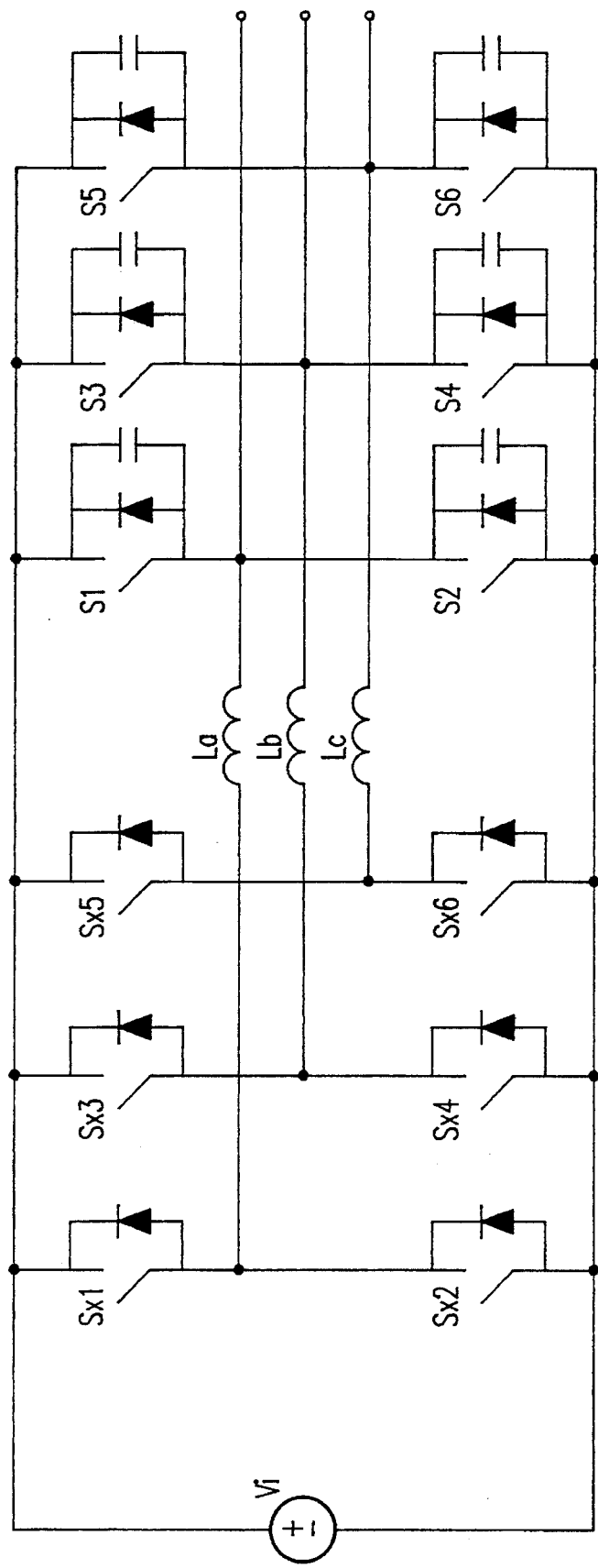
FIG.21
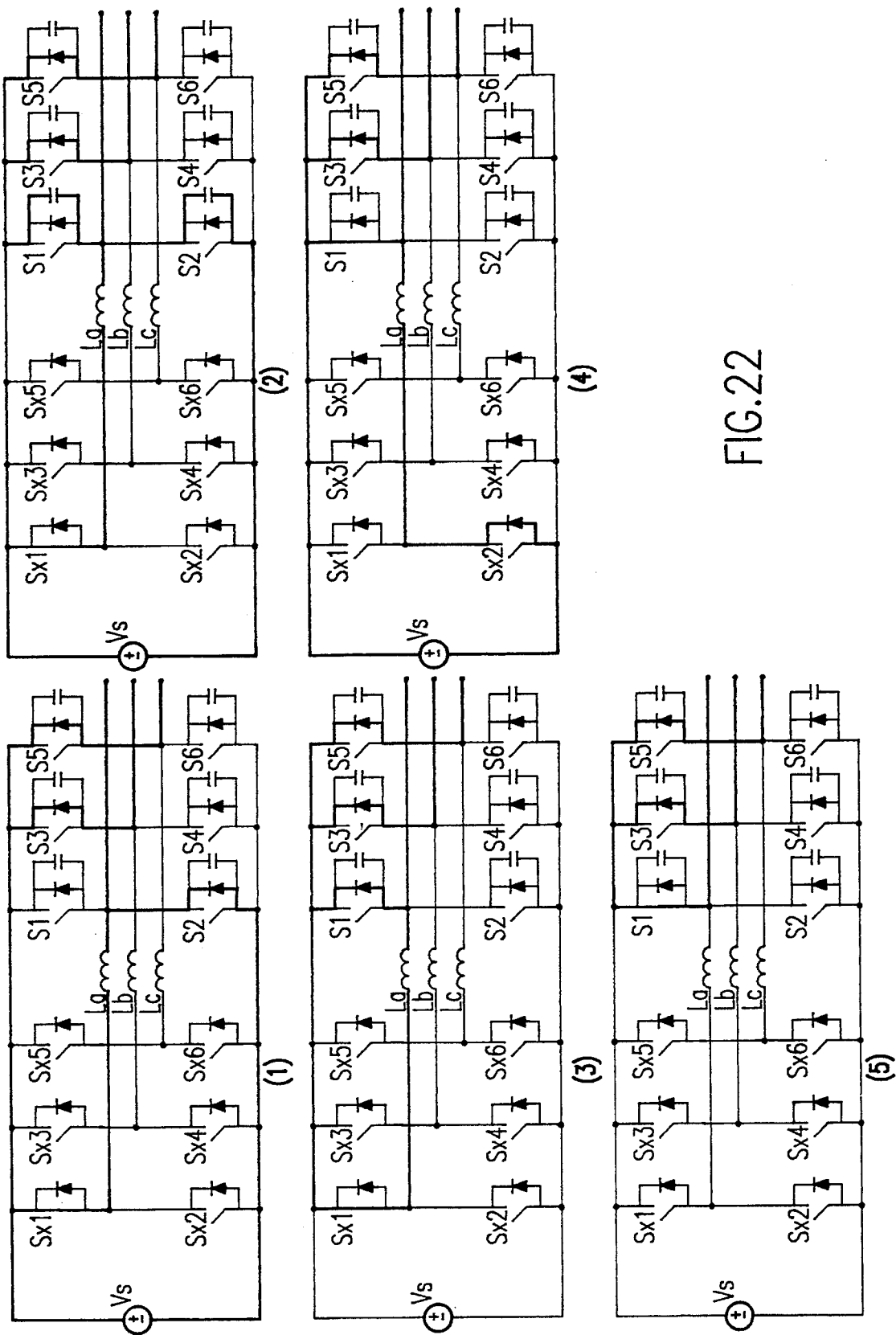
FIG.22
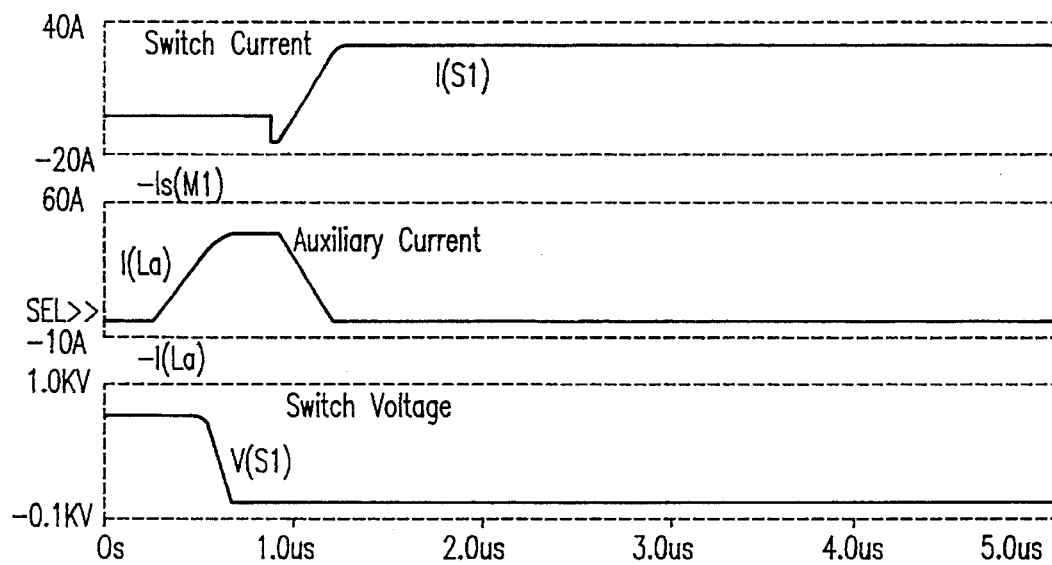
FIG.23

ZERO-VOLTAGE-TRANSITION (ZVT) 3-PHASE PWM VOLTAGE LINK CONVERTERS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to zero-voltage-transition (ZVT), 3-phase voltage link converters (VLC) and, more particularly, to 3-phase voltage link converters in which ZVT can be achieved without affecting the switching modulation scheme of the main power switches.

2. Description of the Prior Art

Three-phase PWM voltage link converters (VLC), including voltage source inverters (VSI), boost rectifiers and voltage source active power filters, are widely used in medium to high power conversion and power conditioning systems. FIG. 1 shows an example of a prior art three-phase VLC. To achieve high performance, low weight, and small size, a high switching frequency is preferred. Unfortunately, high frequency operation seeds severe problems, including, excessive switching losses, diode reverse recovery, and high dV/dt in the load. These problems reduce circuit efficiency, produce high EMI emission, and can cause premature failure of isolation material in electric motors connected to the VLC. To avoid the problems associated with high frequency switching, the switching frequency of most conventional VLC's is usually held below 10 KHz in most high power applications.

It is recognized that high switching frequency losses stem mainly from an abrupt voltage change experienced in the VLC when the active switch turns on. In recent years soft switching techniques, such as zero voltage switching (ZVS), have been developed to reduce switching losses and allow higher switching frequencies to be used. There are many advantages to using ZVS in VLCs. ZVS practically eliminates diode reverse recovery, switch turn-on losses, and allows the use of larger capacitor snubber to reduce switch turn-off losses and dV/dt in output voltage.

Much research effort has been spent on implementing soft switching techniques of VLC in recent years and several ZVS topologies have been proposed. Since most ZVS problems stem from the "stiff" DC bus voltage, most of the ZVS topologies try to "soften" the voltage source by inserting an interface circuit between voltage source and bridge switches. The interface circuit resonates the DC bus voltage to zero before switch turn-on to obtain zero voltage switching. This is the basic concept of DC Link Commutation, used in, for example, resonant DC link inverters (RDCLIs). Although switching losses can be reduced in RDCLIs due to zero voltage switching, other problems have been created such as, for example, high circulating energy, high switch voltage stress, and poor PWM control resolution.

ZVS circuit topologies are known which possess full range PWM control capability. However, the soft switching of inverter switches in these topologies is achieved by an abrupt turn-off of an auxiliary switch on the DC bus. Since this DC bus switch is in the main power path, considerable conduction loss and turn-off loss are introduced. Also, the synchronization of switch turn-on in these topologies results in non-optimum PWM scheme. To remedy these problems a ZVS rectifier with a DC rail diode, which helps to realize DC link soft switching has been introduced in the art. The DC rail diode scheme is very effective but has the disadvantage that it renders the ZVS rectifier only to provide unidirectional power conversion.

A common disadvantage of DC link commutation converters is that some auxiliary device has to be put in the main power path. This can be overcome by putting the soft switching circuit on the AC side of VLC. The normal operation of the AC-side-commutation converters is quite similar to that of their PWM counterparts. The soft switching circuit is active only at the short commutation transient from diodes to switches. This concept is the same as Zero-Voltage Transition (ZVT) technique in DC—DC converters.

Two ZVT topologies include an auxiliary resonant commutated inverter (ARCPI) and a 3-phase ZVT PWM rectifier/inverter as shown in FIG. 2 and FIG. 3, respectively. A major concern is how to simplify the auxiliary circuit 10, and to avoid the extra turn-off loss in the previous three-phase ZVT PWM rectifier/inverter.

In the case of the ARCPI, shown in FIG. 2, the concept of AC side commutation is utilized. This inverter can be controlled according to any PWM scheme with some special switching arrangement for ZVT transition. The operation of soft switching is independent in every phase. Suppose D_1 (the parallel diode of S_1) is conducting and S_2 should be turned on. The ZVT commutation proceeds as follows:

a) At the beginning, S_1 and S_{xa} are turned on. Then resonant inductor L_{xa} will be charged through D_1;

b) When the inductor current reaches load current of Phase A, D_2 is turned off naturally;

c) When the inductor current equals load current plus a "trip" current, S_1 is turned off, and the resonance between L_a and the capacitance of node A begins;

d) When the node voltage V(A) resonates to negative bus voltage, D_2 starts conducting and S_2 can be turned on under zero voltage. After this, L_{xa} is discharged and its current decreases towards zero;

e) S_{xa} is turned off when its current reaches zero; then the ZVS commutation is completed.

ARCPIs have the advantage that auxiliary switches 14 (S_{xa}, S_{xb}, and S_{xc}) need only withstand half of the DC bus voltage and are turned off under zero current condition. However, six auxiliary switches are required and usually not cost effective except in very high power applications.

The ZVT converter shown in FIG. 3 attempts to overcome the drawback of the ARCPIs shown in FIG. 2. The ZVT converter shown in FIG. 3 uses only one auxiliary switch S_x. However, there are some tradeoffs. The most serious being that the ZVT converter cannot operated when three high side switches or three low side switches in the power stage 12 are conducting (i.e. in a zero voltage vector), because no voltage is applied at the ZVT circuit input. To overcome this limitation, a space vector modulation (SVM) scheme has been modified so that the commutation from diodes D_1–D_6 into active switches occurs in all three phases at the same time. For example, if the current in phase A is flowing into the bridge and phase B and phase C currents are flowing out of bridge, then the only turn-on commutation is from D_1, D_4, D_6 to S_2, S_3, S_5. The commutation process is divided into the following steps:

a) At the beginning of the commutation, S_x, S_1, S_4, and S_6 are turned on, so resonant inductor are charged by V_i;

b) Just as in ARCPI, when resonant inductor currents (L_a, L_b, and L_c) reach certain values, S_1, S_4 and S_6 are turned off, so the resonant inductor resonate with the node capacitances (A, B, and C);

c) After all three node voltages (A, B, and C) resonate to opposite rails, S_2, S_3 and S_5 can be turned on under zero

voltage condition. The resonant inductor (L_a, L_b, and L_c) are discharged by V_i in this operation mode;

d) Before any resonant inductor current decreases to zero, the lone switch S_x is turned off. The remaining currents in the resonant inductor continue to be discharged through feedback diodes 16 to zero;

e) After the three resonant inductor currents reach zero, the ZVT commutation is completed, and the converter resumes its normal operation as a conventional PWM converter.

A serious drawback of the aforementioned topologies is that more switching action of the main switches is required to ensure the ZVS condition. As a result, more turn-off losses and control complexity are introduced, thereby limiting efficiency.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an improved zero voltage transition (ZVT) pulse width modulation (PWM) voltage link converter (VLC);

It is yet another object of the present invention to provide a ZVT PWM link converter which can provide zero voltage switching without increasing the switching of the main switches in the converter power stage;

It is yet another object of the present invention to provide a novel circuit topology to recover commutation energy and to discharge resonant inductor currents to zero at the end of each cycle.

According to the invention, in a first embodiment, an improved zero voltage transition (ZVT) pulse width modulation (PWM) link converter is provided which introduces a space vector modulation scheme and an auxiliary circuit which includes a commutation power supply or special switch arrangement used to discharge resonant inductor currents to zero and to recover commutation energy. In an alternate embodiment, an improved zero voltage transition (ZVT) pulse width modulation (PWM) link converter provides an auxiliary switch for each main switch in the converter to achieve ZVT. Both embodiments of the novel ZVT converter provide zero-voltage switching without increasing switching action of the main switches. In this way, the advantages of PWM control is maintained. Conduction loss, turn-off losses, and voltage stress of the main switches are the same as in conventional PWM converters, but the dominant turn-on losses are eliminated, so total power losses are minimized.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects and advantages will be better understood from the following detailed description of a preferred embodiment of the invention with reference to the drawings, in which:

FIG. 1 is a prior art three phase voltage link converter;

FIG. 2 is a prior art auxiliary resonant commutation pole inverter;

FIG. 3 is a prior art zero voltage transition (ZVT) pulse width modulation (PWM) rectifier/inverter;

FIG. 4 is an improved ZVT PWM voltage link converter according to the present invention;

FIG. 5 are drawings showing the three phase voltages and voltage space vectors for a space vector modulation scheme (SVM);

FIG. 6 is a SVM scheme for the circuit shown in FIG. 5 in rectifier mode (where phase A has maximum current);

FIG. 7 is a SVM scheme for the circuit shown in FIG. 5 in inverter mode (where phase A has maximum current);

FIG. 8 is a SVM scheme for sector I shown in FIG. 6 (where phase B has the maximum current);

FIG. 9 is a commutation power supply implemented as an energy feedback circuit;

FIG. 10 is a is a SVM scheme for the circuit shown in FIG. 5 in regenerative mode (where phase A has maximum current);

FIG. 11 is an example of a three phase PWM ZVT boost rectifier according to the present invention;

FIG. 12 is a PWM ZVT boost rectifier according to the present invention;

FIG. 13 is ZVT commutation sub-topologies of the circuit shown in FIG. 12 in rectifier mode;

FIG. 14 is ZVT commutation waveforms for the sub-topologies shown in FIG. 13;

FIG. 15 is a simulation of ZVT commutation;

FIG. 16 is ZVT commutation sub-topologies of the circuit shown in FIG. 12 in regenerative mode;

FIG. 17 are turn-on commutation waveforms for the sub-topologies shown in FIG. 16;

FIG. 18 is a simulation of turn-on commutation;

FIG. 19 is a ZVT 3-level boost converter according to the present invention;

FIG. 20 is a ZVT 3-level PWM boost rectifier according to the present invention;

FIG. 21 is a ZVT PWM voltage link converter for high power applications having an auxiliary switch for each main switch in the converter;

FIG. 22 is sub-topologies of the circuit shown in FIG. 21 for a commutation from D_2 to S_1;

FIG. 23 is a simulation of the commutation from D_2 to S_1.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

Referring now to the drawings, and more particularly to FIG. 4, there is shown an improved ZVT PWM voltage link converter according to the present invention. To reduce converter cost, it is convenient to divide the six main switches into two groups comprising three high side switches and three low side switches. With respect to soft switching, each group can be viewed as a DC—DC converter and use a set of ZVT circuit. In the improved link converter, S_{xd} is used to provide ZVS condition to the three low side switches S_2, S_4 and S_6, while S_{xu} is used to provide ZVS condition to the three high side switches S_1, S_3 and S_5.

The zero voltage switching of the main switches can be achieved under any circumstances, and the control of the converter can be implemented according to any appropriate PWM scheme. Since voltage space vector modulation (SVM) has the advantages of high output voltage, low harmonic distortion, low switching power losses, and easy microcomputer implementation, SVM-based control is preferred. To reduce the actuation of the commutation circuit 20, a modified space vector PWM scheme can be utilized to synchronize the main switch turn-on (S_1–S_6) when possible. This scheme changes switching sequences according to the relative magnitude of phase currents. Take inverter operation as an example. Supposing the reference voltage space vector

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is in the 60° period of Sector I shown in FIG. 5, SVM schemes is as follows:

Scheme (A): If current in phase A or Phase C is larger than currents in the other two phases, then S_1 or S_6 is closed all the time, and the other two phases work in PWM operation. The turn-on of the main switches is easily synchronized. Notice that this scheme also gives minimum turn-off losses of main switches, since the phase with the highest current is not switched. Taking maximum current in phase A as an example, FIG. 6 shows the modulation scheme in the rectifier mode, while FIG. 7 shows the modulation scheme in the inverter mode.

Scheme (B): If phase B has the largest current, then PWM scheme is changed back to standard voltage space vector modulation described in, for example, C. Cuadros et al., *Space Vector Modulation, Zero Voltage Transition Three-Phase DC Bidirectional Converter*, *Proceedings of PESC*, 1994, pp. 16–23, which is herein incorporated by reference, and no turn-on synchronization is used. The commutation circuit 20 has to be actuated more than once in a switching cycle. Because the turn-off number of the main switches is reduced to minimum, the switching losses of the main switches are also minimized.

The modulation scheme of sector I of FIG. 5 is shown in FIG. 8. If phase angle ϕ is smaller than 30°, then only scheme A is to be used. However, with a larger phase angle, scheme B has to be used for a time duration of (ϕ–30°) in 60° interval. The operation of the ZVT auxiliary circuit is explained with two operation examples as follows:

Example A: D_1, D_4 and D_6 are conducting, and D_4 and D_6 are to be switched. This commutation is a typical turn-on commutation in the rectifier operation. The commutation takes the following steps:

(1) At the beginning of commutation, S_{xu} is turned on. Resonant inductor L_b and L_c start to be charged linearly.

(2) When the sum of currents in L_b and L_c reaches the sum of phase B and phase C currents, diodes D_4 and D_6 turn off naturally. After this, L_b and L_c begin to resonate with node capacitances of phase B and phase C, and voltages of nodes B and C increase towards positive DC rail.

(3) When voltages of nodes B and C reach the positive DC rail, D_3 and D_5 start conduction. After this, S_3 and S_5 can be closed with zero voltage, and S_{xu} can be turned off.

(4) After S_{xu} is turned off, L_b and L_c are discharged through D_{xu}, commutation power supply V_{xu}, and DC bus voltage V_s.

(5) When the currents in L_b and L_c are discharged to zero, D_{xu} and the auxiliary diode bridge turn off, and the ZVT commutation is completed.

Example B: S_1, D_3 and D_S are conducting, and D_3 and D_5 are to be switched. This commutation is a typical turn-on commutation in the inverter operation. The commutation process consists of following steps:

(1) At the beginning of the commutation, S_{xd} is turned on. Then resonant inductor L_a, L_b and L_c are charged linearly by the DC rail voltage source V_s, through S_1, D_3, and D_5, respectively.

(2) When the sum of currents in L_b and L_c reaches the sum of currents in phase B and Phase C, D_3 and D_5 turn off naturally. Resonance between L_b, L_c and capacitance of nodes B and C starts. Voltages of nodes B and C resonate towards negative DC rail. The charging of resonant inductor L_a continues until S_{ad} is turned off.

(3) When voltages of nodes B and C reach the negative DC rail, D_4 and D_6 start conduction. After this, S_4 and S_6 can be closed with zero voltage, and S_{ad} can be turned off.

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(4) After S_{xd} is turned off, L_b and L_c are discharged through D_{xd}, commutation power supply V_{xd} and DC bus voltage V_s. Meanwhile, L_a is discharged through D_{xd} and commutation power supply V_{xd}.

(5) When the currents in L_a, L_b, and L_c are discharged to zero, D_{xd} and the auxiliary diode bridge turn off, and the ZVT commutation is completed.

Notice that the commutation processes in Example (A) and Example (B) are similar. The main difference is that the auxiliary current peak in Case B is higher and takes a longer time to be discharged to zero.

As exemplified above, additional commutation power supplies are used to discharge resonant inductor and recovery commutation energy. The power and voltage ratings of commutation power supply are small compared with the main circuit. This power supply can be used to power control circuit and drive circuit, or it can be implemented as an energy feedback circuit which sends the commutation energy to the DC side. FIG. 9 shows an example of a circuit for implementing the commutation power supply V_x as a feedback circuit. After the main switches are turned on, S_x can be turned off. The current in L_x will flow through the commutation power supply V_x, and the energy in L_x is delivered to V_s through coupled inductor L. Capacitor C is used to discharge L after most of the energy in L_x is sent to V_s while D_z and R can damp the oscillation because of leakage inductance L.

The inventive ZVT voltage link converter is very suitable for high and medium power applications because it combines the advantages of zero voltage switching and PWM control with a reasonably simple auxiliary circuit. The basic goal of the new topology is to achieve ZVS without increasing turn-off losses of the main switches in any operation mode. Described below are several variations of the topology tailored for bidirectional rectifiers and high power applications. When a boost rectifier works as a power factor correction (PFC) circuit, its power factor (pf) is always controlled close to zero, i.e. the phase angle between phase current and phase voltage is very small. Because the relation between phase current and phase voltage is quite fixed, the control and soft switching scheme can be simplified. First, the space vector PWM scheme can be implemented in a simpler way as follows:

(A) Rectifier Mode: In the rectifier mode, the phase with maximum current is clamped to DC bus all the time, and the other two phases are controlled with PWM. For example, in Sector I shown in FIG. 5, if phase A has maximum current, then S_1 is kept on so that D_1 is always conducting. S_3 and S_5 are controlled in a PWM way with their turn-on synchronized, i.e. the turn-on commutation is always from D_4 and D_6 to S_3 and S_5. With this kind of control, the turn-off losses are minimized. The SVM scheme can be exemplified by FIG. 6.

(B) Regenerative Mode: In the regenerative mode, the polarities of the three phase currents are reversed. The modulation scheme is modified to synchronize active switch turn-on in three phases, and complementary voltage vectors are used to synthesize zero vector. This is the same SVM scheme as is shown in FIG. 10 with the same conditions as in Example (A). In this mode, more switching of the main switches S_1–S_6 have been introduced, so more turn-off losses will be produced than in a normal SVM PWM converter. However, since turn-on instances of all switches are synchronized, zero voltage switching can be used more easily to reduce turn-on losses. Hence, the total switching losses in a soft switching converter are still lower than in a normal SVM PWM converter

Referring now to FIG. **11**, for the above SVM schemes, the ZVT circuit can be further simplified. Note that switch turn-on commutation always starts with three diodes conducting, and the diodes in one group (high side or low side) are always turned off at the same time, the resonant inductor can be shifted into the auxiliary diode bridge and combined into one L_x. Thus only one auxiliary switch S_x, auxiliary diode D_x, and commutation power supply V_x are needed.

The topology shown in FIG. **11** works well with a the commutation power supply V_x. However, for some applications, it may be desirable to replace the additional commutation power supply and send commutation energy to output directly. Referring now to FIG. **12**, the operation principle of this topology is exactly the same as that of FIG. **11**, with the only difference of implementing S_x with two switches (S_{x1} and S_{x2}) so that L_x can be discharged by V_s directly at the end of the ZVT commutation. Assuming that before commutation, voltage space vector is in Sector I as is shown in FIG. **5**. With the above discussed space vector modulation scheme, two types of turn-on commutation exist for the ZVT boost rectifier shown in FIG. **12**:

(A) Rectifier Mode—from D_4 and D_6 to S_3 and S_5: Suppose D_1, D_4 and D_6 are conducting with maximum current in D_1 and S_3 and S_4 are to be turned on. The whole commutation process is shown in FIG. **13** and FIG. **14**. Notice that switch S_1 is kept on during the whole commutation. The commutation process consists of the following stages:

(1) [t_0, t_1] Auxiliary switches S_{x1} and S_{x2} are turned on at t_1, so the resonant inductor L_x is charged by output voltage V_s, and its current increases linearly.

(2) [t_1, t_2] When the current I_{Lx} reaches the sum of load currents in Phase B and Phase C at t_1, diodes D_4 and D_6 turn off naturally and L_x starts resonance with node capacitance of Phase B and C. The voltages of nodes B and C increase towards positive DC rail in a resonant manner.

(3) [t_2, t_3] When the voltages of nodes B and C reach the DC rail voltage at t_2, body diodes D_3 and D_5 start conduction, so the current in L_x freewheels through S_1, D_3, and D_5. Because of the clamp action of D_3 and D_5, switch voltages of S_3 and S_5 are kept at zero.

(4) [t_3, t_4] After t_2, S_3 and S_5 can be turned on with zero voltage condition, therefore eliminating turn on losses and diode reverse recovery. At the same time, S_{x1} and S_{x2} can be turned off and the commutation energy in L_x is fed into V_s through D_{x1} and D_{x2}. Meanwhile, L_x is discharged by V_s towards zero current.

(5) [t_4, t_0] When the resonant inductor current decreases to zero at t_4, D_{x1} and D_{x2} turns off naturally. Now the ZVT commutation is completed, and the auxiliary circuit keeps inactive until the next ZVT commutation.

FIG. **15** shows simulation results of the commutation process for the circuit shown in FIG. **12** in rectifier mode. Notice that no overlap between switch voltage and switch current in S_3 and S_5 exists, so turn-on losses are eliminated completely.

(B) Regenerative Mode—from D_2, D_3 and D_5 into S_1, S_4, and S_6: Suppose that the voltage space vector is still in Sector I with D_2, D_3 and D_5 conducting, and S_1, S_4 and S_6 are to be turned on. The commutation process is shown in FIG. **16** and FIG. **17** as follows:

(1) [t_0, t_1] The turn-on commutation starts with S_{x1} and S_{x2} being turned on at t_0. After auxiliary switches are turned on, L_x is charged by the output voltage through the three conducting diodes, and its current increases linearly.

(2) [t1, t2] When the current I_{Lx} reaches maximum load current (here phase A current), the three diodes turn off naturally, and L_x starts to resonate with node capacitance of nodes A, B, and C. the three node voltages resonate towards their opposite DC rails respectively.

(3) [t2, t3] When the three node voltages become equal (in this case ⅔ of output voltage), the auxiliary diode bridge **30** is shorted and the resonance ends. The current in L_x freewheels through S_{x1}, S_{x2}, and the shorted diode bridge **30**.

(4) [t3, t4] After t_2, all diodes in the main bridge stop conducting. Also, the voltage across S_1 is reduced to $V_s/3$, and the voltages across S_4 and S_6 are both reduced to $2\,V_s/3$. Active switches S_1, S_4 and S_6 can be turned on with reduced voltages at t_3. At the same time, S_{x1} and S_{x2} should be turned off, so L_x is discharged by V_s through D_{x1} and D_{x2} in this stage.

(5) [t4, t5] When the current in L_x is discharged to zero at t_5, D_{x1} and D_{x2} turn off naturally. The commutation is completed, and the auxiliary circuit keeps inactive until the turn-on commutation in the next switching cycle.

FIG. **18** shows simulation results for the commutation process for the circuit shown in FIG. **12** in regenerative mode. Because diode reverse recovery is eliminated and turn-on voltages are reduced, the turn-on losses are largely reduced due to the "partial" soft switching condition, so high efficiency can still be achieved in regenerative mode.

Referring now to FIGS. **19** and **20**, the above concept can be extended to a three-level boost rectifier. The main advantage of three-level rectifier is that the voltage rating of active switches can be reduced compared to conventional boost rectifiers. Also, its control can be implemented as three independent phase controllers with turn-on instances synchronized in three phases. The ZVT circuits work in a similar way to that in FIG. **12** operating in regenerative mode. Before turn-on of the main switches, S_1, S_2, and S_3, auxiliary switches (S_x in FIG. **19** or S_{x1} and S_{x2} in FIG. **20**) are turned on. The resonant inductor L_x will be charged through the conducting diodes D_1–D_6. After the current in L_x reaches load current, the diodes D_1–D_6 will turn off softly, thus eliminating the reverse diode recovery problem. After this, the voltages across the main switches can be resonated to zero by L_x and so to allow S_1–S_3 to turn on with zero voltage. Thereafter, the auxiliary switches are turned off and the energy in L_x is delivered to the output through feedback diodes **41**. The operation of the circuits shown in FIGS. **19** and **20** is very similar except that the auxiliary switches in FIG. **20** need only withstand only half output voltage, making the circuit very attractive for high voltage applications. Note that the control of each main switch can be the same as in a single phase boost rectifier.

Referring now to FIG. **21**, there is shown an alternate embodiment of the present invention. In the first embodiment, auxiliary switches and additional commutation power supply means are used to discharge resonant inductors and recovery commutation energy. In some high power applications the auxiliary power supplies may be eliminated by using additional auxiliary switches; one for each main switch. In this case, the topology shown in FIG. **21** can be used. Compared with the auxiliary resonant commutation pole inverter (ARCPI), the operation and auxiliary switch count of the new topology is similar but has the significant advantage in that the resonant inductor current no longer needs to be charged higher than load current, Hence, no extra main switch switching is necessary to achieve ZVS turn-on and no extra current peak in auxiliary switch is experienced. Also, the control timing in ZVT transition is

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not critical because zero voltage condition can be maintained as long as desired.

The ZVT commutation of this topology is independent for every active switch and its control is almost the same as in ZVT DC—DC boost converter. For example, if D_2 is conducting and is to be switched, then the ZVT commutation is shown in FIG. 22 and will take the following steps:

(1) S_{x1} is turned on at the beginning of commutation. Then the current in inductor La is charged through D_2, S_{x1}, and DC link voltage.

(2) When auxiliary current reaches phase A current, D_2 is turned off naturally. The inductor La starts resonating with node capacitance. The voltage of node A resonates towards positive DC rail.

(3) When node A voltage reaches positive DC rail, D_1 starts to conduct. Auxiliary current freewheels in the path of D_1, La and S_{x1}. Then S_1 can be turned on under zero voltage conditions, and S_{x1} can be turned off.

(4) After S_{x1} is turned off, inductor La is discharged by DC bus voltage through S_1 and D_{x2} (the parallel diode of auxiliary switch S_{x2}).

(5) When current of inductor La decreases to zero, D_{x2} turns off naturally and the commutation is completed.

A simulation of this commutation process is shown in FIG. 23, which indicates clearly that zero voltage switching has been achieved since switch voltage decreases to zero before switch current increases. Thus, turn-on loss and reverse recovery are eliminated.

While the invention has been described in terms of a single preferred embodiment, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.

We claim:

1. A zero-voltage-transition three-phase voltage link converter, comprising:

a direct current power source;

a main switching circuit connected between said direct current power source and a three-phase alternating current output; and

an auxiliary circuit connected between said direct current power source and said main switching circuit, said auxiliary circuit comprising:

at least one resonant inductor connected to at least one phase of said three-phase output;

auxiliary power supply means for discharging said resonant inductor; and

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switch means for switchably connecting said auxiliary circuit to said direct current power source.

2. A zero-voltage-transition three-phase voltage link converter as recited in claim 1 wherein said auxiliary power supply means is an independent power supply.

3. A zero-voltage-transition three-phase voltage link converter as recited in claim 1 wherein said auxiliary power supply means is a feedback circuit inductively coupling said resonant inductor to said direct current power supply through an inductive coupling.

4. A zero-voltage-transition three-phase voltage link converter as recited in claim 1 wherein said auxiliary power supply means is implemented with said direct current power supply connected to said resonant inductor through a pair of cross-coupled diodes.

5. A zero-voltage-transition three-phase voltage link converter as recited in claim 1 further comprising a diode bridge electrically connected between said auxiliary power supply means and said switch means.

6. A zero-voltage-transition three-phase voltage link converter as recited in claim 1 wherein said auxiliary circuit further comprises:

one resonant inductor for each phase of said three-phase output;

a plurality of auxiliary power supply means for discharging said resonant inductors; and

a plurality of switch means for switchably connecting said auxiliary circuit to said direct current power source.

7. A zero-voltage-transition three-phase voltage link converter, comprising:

a direct current power source;

a main switching circuit having three pairs of power switches connected in parallel with said direct current power source, each of said pairs of power switches corresponding to one phase of a three-phase alternating current output;

an auxiliary circuit for achieving zero voltage transition in said main switching circuit, said auxiliary circuit comprising:

three pairs of auxiliary switches connected in parallel with said direct current power source, each of said pairs of auxiliary switches corresponding to one phase of said three-phase alternating current output, and each of said pairs of auxiliary switches connected to a corresponding one of said pairs of power switches with a resonant inductor.

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